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INTERIM DEVELOPMENT REPORT: ENGINEERING-SCALE HTGR FUEL PARTICLE CRUSHER

by
J. W. BAER and J. B. STRAND

**Prepared under
Contract EY-76-C-03-0167
Project Agreement No. 53
for the San Francisco Operations Office
Department of Energy**

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GENERAL ATOMIC COMPANY

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ABSTRACT

During the reprocessing of HTGR fuel, a double-roll crusher is used to fracture the silicon carbide coatings on the fuel particles. This report describes the development of the roll crusher used for crushing Fort-St.-Vrain type fissile and fertile fuel particles, and large high-temperature gas-cooled reactor (LHTGR) fissile fuel particles. Recommendations are made for design improvements and further testing.

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SUMMARY

The reprocessing of HTGR fuels will involve use of a double-roll crusher to crush the TRISO coated fuel particles. This allows subsequent combustion in a fluidized-bed burner, which removes the inner carbon coatings and converts the metal carbides to oxides.

Experimental work was performed with two double-roll crushers that were identical except for the roll sizes, which determine the crushing gap. Satisfactory fracturing of the silicon carbide coatings of Fort St. Vrain (FSV) and large high-temperature gas-cooled reactor (LHTGR) TRISO fuel particles was demonstrated. The following observations and recommendations are offered as a result of the initial testing:

1. Fuel particle crushing can be accomplished within acceptable burner feed requirements using a nonadjustable roll gap in a disposable crusher module.
2. Side plate wear is more severe than roll wear, and occurs at a higher rate than anticipated.
3. Roll bearings must be protected from crushing dusts by use of high performance seals or barrier systems. These methods and others that will keep debris away from the roll bearings should be examined and tested.
4. Roll bearing preloads are vital to maintaining precise roll gaps. Excessive preloads are detrimental to bearing life.

5. The double-roll particle crusher is sensitive to tolerances during manufacture and assembly. A simpler, advanced design that separates bearing loading from the frame is recommended.
6. Crushing of silicon carbide or an equally abrasive material should continue until roll wear trends can be established.

1. INTRODUCTION

Using unirradiated fuels, General Atomic Company is developing a high-temperature gas-cooled reactor (HTGR) fuel reprocessing pilot plant. This work is a part of the National HTGR Fuel Recycle Development Program, under the direction of the Department of Energy. The overall objective of the program is to demonstrate the technology for recycling HTGR fuels by using the Th/U-233 fuel cycle for future safe operation of a commercial plant.

Equipment and process demonstrations will be done in the cold pilot plant to obtain data for the design and operation of an HTGR reference recycle facility (HRRF). The pilot plant systems include the dry head-end processes, in which:

1. Fuel elements are reduced in size by crushing.
2. Element and matrix graphites are removed by combustion in a fluidized bed.
3. Fissile and fertile particles are separated by pneumatic classification.
4. The silicon carbide coatings of the TRISO fuel particles are broken in a crusher.
5. The inner carbon coatings are removed, and the metal oxycarbides are converted to oxides by combustion in a fluidized bed.

The fissionable materials are recovered in the wet head-end processes, then refabricated into fuel.

This report describes the tests done on the engineering-scale fuel particle crusher to date.

Fuel particles enter the crusher by gravity flow from its feed bunker. The crushing action is produced from contact between the surfaces of two counter-rotating rolls and the fuel particles. This forces the particles through a narrow gap between the rolls. The gap is precisely set for each type of particle so that the silicon carbide coating is broken without overcrushing. This produces a product that is easily fluidized in the burner. The crushed particles gravity flow into the burner feed hopper.

Testing to date has included determination of (1) throughput rates, (2) start-under-load capabilities, (3) product size distributions, (4) roll gap requirements, and (5) quantity of unbroken particles. Fissile and fertile FSV fuel particles and LHTGR TRISO fissile particles have all been successfully crushed.

2. REQUIREMENTS

The reprocessing of HTGR fuel requires the fracture of the outer silicon carbide coating of fuel particles to expose the inner carbon coatings and carbides for fluidized-bed combustion.

The fuel particle crusher must accept carbide-coated fuel and must crack but not crush the carbide shells. It provides the secondary burner feed with a minimum size distribution of approximately 160 μm volume-to-surface diameter at a rate of at least 30 kg per hour from 60 kg batches. This is to be accomplished safely in a semicontinuous fashion in compact, long-life equipment that can be readily maintained or replaced when the limit of 1% unbroken fuel particles is exceeded. The equipment must start when fully loaded and operate in the environment of a hot cell.

Detailed requirements for the equipment may be found in Ref. 1.

Test objectives of the test program as defined in Ref. 2 were to validate the equipment to meet the design, performance, material safeguard, health, and safety requirements and to determine the suitability of the fixed gap, double-roll crusher for a hot reprocessing facility. Testing was accomplished in three phases:

- Phase I - Demonstration of roll crusher with FSV-type fertile fuel particles
- Phase II - Demonstration of roll crusher with FSV-type fissile fuel particles
- Phase III - Demonstration of roll crusher with LHTGR-type fissile fuel particles

Preoperational testing was performed to determine proper roll gaps and appropriate roll bearing preloads to maintain the roll gap.

Additional ongoing testing is achieved while the equipment is operated to provide feed material for the testing of the secondary burner and for head-end sequential burns.

3. EQUIPMENT DESCRIPTION

The fuel particle crusher is a small, compact, double-roll crusher with a fixed crushing gap. The crushing rolls are 10 cm (4 in.) in diameter by 10 cm (4 in.) long, and they are made of hardened steel. It operates semicontinuously in-line with the solids handling system to produce feed for the secondary burner. Figure 1 shows the fuel particle crusher and drive motor mounted in place on the secondary burner hopper. The double-roll fuel particle crusher, shown schematically in Fig. 2, is described in detail in Ref. 1.

Fuel particles enter the fuel particle roll crusher by gravity flow from the particle crusher feed bunker. The crushing action is produced by the contact between the two counter-rotating roll surfaces and the fuel particles, which forces the fuel particles through the narrow gap between the rolls. The crushed fuel particles are discharged by gravity into the secondary burner feed hopper. The 10-cm (4-in.) diameter rolls, driven by a variable-speed drive system, are contained in an enclosure that connects the crushing system to the particle crusher feed bunker and the secondary burner feed hopper. This enclosure prevents loss of fuel particles, fragments, and dust. The configuration of the rolls and the enclosure assembly precisely determines the crushing gap between the rolls and assures that all of the fuel particles will pass through the roll gap. The roll gap can only be altered by replacing the rolls with rolls of different diameters.

In normal crusher operation, the drive motor is activated, the drive controller is set for the desired roll rpm (read on a speed indicator), and the rolls are allowed to reach the desired speed. The fuel particles are batch-charged by opening a knife gate valve in the discharge outlet of the particle crusher feed bunker; they are choke-fed by gravity to the

Fig. 1. Fuel particle crusher and drive motor (mounted on secondary burner feed hopper)

Fig. 2. Double-roll particle crusher

crushing area, where the silicon carbide coatings of the particles are fractured. The crushed material is then discharged into the burner feed bunker.

4. FSV FERTILE PARTICLE CRUSHING

This particle crusher, which is driven by a 560-W (3/4 hp), variable-speed dc electric motor with a 40:1 reducer, has demonstrated the ability of a double-roll crusher to successfully process FSV fertile and fissile fuel particles. It is fully operational, and it has been used in the preparation of feed material for the secondary burner. The following discussion summarizes its development activities to date.

Phase I of the activity plan (Ref. 2) for the fuel particle crusher was completed successfully, demonstrating the ability of the double-roll crusher to process FSV fertile fuel particles. Tests were performed utilizing representative feed lots split from a single larger lot. The tests were arranged so that actual crusher performance could be compared with the performance requirements of the particle crusher design criteria (Ref. 3). A comparison of the individual performance requirements of the design criteria with the actual test results is given below.

The double-roll crusher was required to process fuel particles at a minimum rate of 30 kg/h. Tests proved the throughput rate to have a linear relationship with roll speed. Throughput rates of 50, 101, and 148 kg/h resulted from roll speeds of 25, 50, and 72 rpm. In each case, the product size distributions were virtually identical (see Fig. 3) even though the throughput rates varied by factors of two and three.

If the double-roll crusher is shut down during operation, it must have sufficient power to be restarted without removing the feed material remaining in the crusher. Several tests were performed with feed material in the crusher prior to startup. No significant differences were observed in crusher starting characteristics or in product size distribution for the two load cases.

Fig. 3. Fuel particle crusher product size distributions for various throughput rates

The crusher product must contain less than 1% unbroken particles. Throughout the test program, unbroken particles were found in small quantities in the upper two size categories ($>500 \mu\text{m}$ and $>425 \mu\text{m}$). The maximum amount of unbroken particles found in all the tests was estimated at less than 0.1%.

The size distribution requirement for the crusher product is $160 \mu\text{m}$ minimum volume-to-surface diameter. To describe usefully the size distribution of a batch of solid particles, the size distribution functions P and p were defined as follows (Ref. 4). Let P be the volume fraction (or weight fraction or numbers fraction) of particles smaller than size d_p and let $pd(d_p)$ be the volume fraction (or weight fraction or numbers fraction) of particles of size between d_p and $d_p + d(d_p)$. P gives the cumulative distribution of sizes and is dimensionless, while p gives the distribution directly and has units of reciprocal length.

The relationship between p and P is found by considering particles of any particular size d_{p_1} , for which

$$p_1 = \left(\frac{dP}{d(d_p)} \right)_1 \quad \text{or} \quad P_1 = \int_0^{d_{p_1}} pd(d_p) \quad .$$

For discrete distribution of particles with equal or unequal intervals of size (sieve analysis produces a discrete distribution of unequal size intervals), the relation between p and P at any d_{p_i} is

$$p_i = \left(\frac{\Delta P}{\Delta d_p} \right)_i \quad \text{or} \quad P_i = \sum^i (p \Delta d_p)_i = \sum^i x_i \quad ,$$

where x_i is the fraction of material in size interval i .

With the size distribution of particles defined, the specific surface and mean diameter of a mixture of different-sized particles of a given shape may be found. For pressure drops in flow through beds (a variable

in secondary burner fluidization), the surface area of the particles is the prime consideration. Thus, mean sizes and shapes are defined such that for a given mass of solid, the surface area remains constant. Using the size distribution, the mean specific surface is defined as

$$\bar{a}' = \sum_{\text{all } i} a'_i (p\Delta d_p)_i = \frac{6}{\phi_s} \sum_{\text{all } i} \frac{(p\Delta d_p)_i}{d_{p_i}} = \frac{6}{\phi_s} \sum_{\text{all } i} \left(\frac{x}{d_p}\right)_i$$

for a discrete distribution. Since the mean specific surface defined in terms of mean diameter is

$$\bar{a}' = \frac{6}{\phi_s \bar{d}_p} ,$$

the mean diameter becomes

$$\bar{d}_p = \frac{6}{\phi_s \bar{a}'} = \frac{1}{\sum_{\text{all } i} \left[(p\Delta d_p)_i / d_{p_i} \right]} = \frac{1}{\sum_{\text{all } i} (x/d_p)_i} .$$

For mixtures of particles of different sizes and shapes, $\bar{d}_p$ and d_p are replaced by $\bar{\phi_s d_p}$ and $\phi_s d_p$, respectively. Since the shape factors (ϕ_s) are unknown in our size distribution, the shape factors are assigned the value of unity for ease of calculation. The mean diameter ($\bar{d}_p$) is termed the volume-to-surface diameter (d_{vs}) since the surface area is the prime consideration. A description of how the equation for the volume-to-surface diameter,

$$d_{vs} = \frac{1}{\sum \left(\frac{x}{d}\right)} ,$$

is used for a given particle batch is given in Ref. 5.

The main objective of the Phase I tests was to determine the roll gap at which the product size distribution meets the 160- μm requirement. The proper roll gap was approached from the low side at 25.4- μm (0.001-in.)

intervals. The final three tests at a roll gap of 480 μm (0.019 in.) produced volume-surface diameters greater than 160 μm . At successively smaller roll gaps, smaller volume-surface diameters were obtained. Figure 4 shows the product size distributions for various roll gaps.

The roll gap selected for crushing the Fort St. Vrain fertile fuel particles was 480 μm (0.019 in.).

Upon completion of the Phase I testing of the fertile particle crusher (and after processing approximately 150 kg of FSV fertile fuel particles), it was found that the amount of unbroken fuel particles had risen from <1% to >2% by weight. The allowance for unbroken particles was established by Ref. 3 at <1% by weight for secondary burner feed.

The crusher was disassembled to determine the reason for this increase in unbroken fuel particles. No apparent evidence of wear on the roll crushing surfaces or on the roll ends was found, and there was no evidence of spalling, gouging, or galling on any wearing surface. However, each side body plate showed extensive erosive wear in the region opposite the crushing region at the ends of the roll pairs (see Fig. 5). The wear pattern was a groove approximately 0.3 mm (0.012 in.) deep by 0.6 mm (0.025 in.) wide by 7.9 mm (0.31 in.) long in each side plate. Two grooves of this size and a roll gap of 0.48 mm (0.019 in.) would be sufficient to pass uncrushed fuel particles 0.51 to 0.56 mm (0.020 to 0.022 in.) in diameter. This would account for approximately 2% unbroken particles.

The wear grooves were filled with a ceramic coating material, chromium oxide, which was applied to the wear area by plasma spraying. This material has an equivalent hardness of R_c 74 compared with the side plate hardness of R_c 57 and the roll hardness of R_c 58. There was no local reduction in side plate hardness resulting from the plasma spray coating application.

Fig. 4. Fuel particle crusher product size distributions for various roll gaps

Fig. 5. Particle crusher side plate showing wear groove after 150 kg of throughput

After crushing one 60 kg batch of fuel particles, this ceramic chromium oxide coating wore excessively, and a tungsten carbide sprayed coating was tried. It, too, was unsuccessful when a 60 kg batch was crushed.

The side bodies were next slotted by electrical discharge machining (EDM), and inserts of high-density, cemented tungsten carbide were embedded in the slots. Each side plate contained a different candidate insert material for comparative evaluation purposes. These materials have hardnesses typically equivalent to R_c 80 to 83, as compared with the plasma-sprayed chromium oxide at R_c 74 and the tungsten carbide composites at R_c 60 to 70. One side plate with the tungsten carbide insert is shown in Fig. 6.

The FSV fertile particle crusher was then used to prepare feed for four burner runs on the 0.20-m secondary burner. The total throughput was 240 kg. The roll gap setting was 480 μ m, and the roll speed was between 36 and 44 rpm. The crushing efficiency was >99.9% for each run.

The localized wear on the crusher body side plates continued. The inserts of tungsten carbide composites K703 and K68 were tested simultaneously, crushing 150 kg of material. Both tungsten carbide inserts exhibited improved wear resistance, with the K703 proving to be the better material.

The K68 insert was removed and replaced with a solid ceramic material, boron carbide (B_4C), which has outstanding hardness (2750 Knoop) compared with tungsten carbide (1800 Knoop). Particle crushing continued with the crusher equipped with the new B_4C insert and retaining the previously installed K703 insert for continued wear information. There has been little evidence of additional wear to either insert since crushing was restarted.

Table 1 lists the various test materials used in the crusher body side plates and gives the wear test results obtained from crushing silicon-carbide-coated fuel particles.

Fig. 6. Fertile crusher side body with tungsten carbide insert

TABLE 1
SIDE BODY WEAR DATA, FERTILE PARTICLE CRUSHER

Material	Source and Type	Hardness (a)		Abrasion Resistance (b)	Observed Wear	Crusher Throughput	Comments
		R _C	R _A				
Tool steel	AISI D2	57	79	13 to 14	Slot, 0.3 mm (0.012 in.) deep x 0.6 mm (0.025 in.) wide	150 kg	As designed
Chromium oxide, plasma spray	Metco 136F - repair	74	89	Unknown	100% removed	60 kg	No binder
Tungsten carbide, plasma spray	Metco 73F - repair	60	81	Unknown	>90% removed	60 kg	Best plasma spray product - cobalt binder
Tungsten carbide, plasma spray	Metco 71VF - repair	53	78	Unknown	100% removed		Comparison material - cobalt binder
Tungsten carbide, and chromium oxide, solid ceramic	Kennametal K703 - insert	80	92	760	Slot, 0.1 mm (0.0044 in.) deep x 0.6 mm (0.055 in.) wide	150 kg	Cobalt binder, best composite material
Tungsten carbide, solid ceramic	Kennametal K68 - insert	>80	93	300	Slot, 0.2 mm (0.0073 in.) deep x 0.7 mm (0.028 in.) wide		Cobalt binder
Boron carbide, solid ceramic	Norton Co. B ₄ C insert	2750 Knoop (c)		Unknown (d)	Traces, (e) not measured	180 kg	None

(a) From vendor data, except D2 tool steel which was hardness tested.

(b) Abrasion resistance equals unity divided by volume loss with dry silica sand - Kennametal data.

(c) For comparison, solid tungsten carbide = 1880 Knoop and solid silicon carbide = 2480 Knoop.

(d) Material used in sand blast nozzles.

(e) Product continues to be acceptable after crushing.

The boron carbide (B_4C) insert implanted in one side plate in the region of highly localized wear was closely examined after 180 kg of particles were crushed. The surface of the insert appeared to be burnished in a characteristic pattern, but the wear was not measured. The other insert of K703 material did not show evidence of any measurable additional wear.

5. FSV FISSILE PARTICLE CRUSHING

The pilot plant experimental plan also called for the development of a crusher to remove the SiC coatings from the FSV fissile fuel kernels. The crusher developed for this purpose was the same double-roll type used to crush fertile particles, but with different roll diameters. Some difficulties were encountered in flame hardening the crushing surfaces of the four crusher rolls (including two spares) to the desired hardness of R_c 58 to R_c 60. Figure 7 shows the results obtained by flame hardening the process control and production control specimens. The latter were processed along with the crusher rolls after the correct processing parameters had been verified with the process control specimens. It can be seen from the figure that process control specimen A was not hard enough, but the situation was corrected and verified by specimen B. The hardness of production control specimens 2 and 6 was at or above the desired minimum hardness of R_c 58 to the required depth of 1.78 mm (0.070 in.). Specimen 4 retained the desired hardness to an acceptable depth of 1.27 mm (0.050 in.).

Inspection of the finished rolls by a dye penetrant technique revealed the presence of fine, intermittent, small circumferential cracks at a common location at the identical end of two of the four rolls purchased. The rolls were accepted for installation after consideration of the crack severity and location and the anticipated roll service. The crushing surfaces of the four rolls were scanned using a surface analyzer, and the surface profiles and surface finishes were documented for future comparative wear determinations.

Problems encountered during construction required imposing 100% inspection on all parts of the assembly. Substantial reworking of components was necessary to obtain hardware built to engineering specifications.

Fig. 7. Effect of flame hardening on process control and production control specimens

5.1. DEVELOPMENTAL TESTING

Phase II testing of the fuel fissile particle crusher was successfully completed. The nominal roll crusher gap required to maximize both crushing efficiency and crushed particle size was 250 μm (0.010 in.).

When initially received, the roll crusher nominal gap was 230 μm (0.009 in.). This was changed to a nominal 330 μm (0.013 in.) gap for the first crushing tests by switching appropriate rolls. A 200-g sample of FSV fissile particles (see Fig. 8 for size distribution) was processed at that time. Approximately 50% of the particles were uncrushed; therefore, a smaller roll gap [280 μm (0.011 in.)] was assembled.

At this gap setting, a study was done on the rotating roll torque versus roll gap to establish the correlation between radial bearing preload and the crushing gap between the rolls. The radial preload of a tapered roller bearing is created by the relative axial position of the inner and the outer bearing elements or races acting on the conical surfaces of the tapered rollers. The amount of radial preload is increased as the two races are brought more closely together. In the particle crusher, these relative positions are regulated by shims which position the outer bearing race. Thinner shims produce higher preloads.

During this study, shim thicknesses were varied 25 or 50 μm (0.001 or 0.002 in.) and the bearing preloads were measured by rotating each independent roll in the assembled crusher at a constant speed using a calibrated torque wrench and noting the rolling torque. The roll gap was gauged by manually roll-reducing a solid, tin-lead soft solder wire [Sn-60, 787 μm (0.031 in.) diameter]; accurately measuring the resultant ribbon thickness in three places; and averaging the results.

Figures 9 and 10 show the results of the preload study for each of the rolls in the crusher assembly. It should be noted in each figure that a rolling preload torque of 0.92 to 1.04 m-kg (80 to 90 in.-lb) is required

Fig. 8. Feed and product size distributions, FSV fissile particle crusher

Fig. 9. Preload torque and solder thickness versus shim thickness, roll 5211011-13, S/N 4340-5

Fig. 10. Preload torque and solder thickness versus shim thickness, roll 5211011-10, S/N 4340-2

to eliminate variances in the preload created by bearing seating, etc. However, viewing the changes in solder thickness with shim thickness, it would appear for both rolls that a preload of 0.26 m-k_g (40 in.-lb) torque* would produce a constant and consistent roll gap of from 280 to 292 μm (0.0110 to 0.0115 in.). The preload selected for future particle crushing was 1.04 m-k_g (90 in.-lb). This proved to be too high for satisfactory bearing life.

Referring to Figs. 9 and 10, it can be seen that repeatable roll gap measurements were made using proper preload shimming and 787 μm (0.031 in.) diameter solid solder. These gap measurements were consistent to within 13 μm (0.0005 in.) and were only 13 to 18 μm (0.0005 to 0.0007 in.) higher than the crusher roll gap calculated from inspection data for this crusher.

A 100-g sample of FSV fissile particles was processed yielding about 3% uncrushed particles. The roll gap following crushing was again 280 μm (0.0110 in.) using the solder strip. Thicker solder [3302 μm (0.13 in.)] was then used. This was extruded to 330 μm (0.013 in.). Since the smallest fuel particle was 300 μm (0.0116 in.) and about 3% were uncrushed, it is reasonable to assume that the gap during highly loaded crushing conditions is greater than the 280 μm (0.0110 in.) measured with the small solder strip. The large solder strip results tend to confirm this, as the larger strips are a definite load on the rolls when extruded through the rolls.

The rolls were again changed to yield a nominal 250 μm (0.010 in.) gap. The roll torque was adjusted to 1.04 m-k_g (90 in.-lb). The gap as measured by the 787 μm (0.031 in.) solder was 250 μm (0.010 in.) while the thicker 3302 μm (0.13 in.) solder yielded a 305 μm (0.012 in.) gap. The resulting crushing efficiency with 200 g of particles was 100%.

The size distribution of these fully crushed FSV fissile fuel particles is shown in Fig. 8. The product angle of repose was 43°. The bulk density was 1.4 Mg/m³ and the tap density was 1.8 Mg/m³. The

*This was subsequently verified by the bearing manufacturer.

throughput of the material was 80 kg/h at 43 rpm roll speed. Start under load was achieved. Normal power draw at 43 rpm roll speed with choke feed conditions is 522 W.

A burner run will be made on the 0.10-m secondary burner using FSV fissile particles processed through the roll crusher using a nominal 250- μ m roll gap.

5.2. DEMONSTRATION OF LHTGR WAR FISSILE FUEL PARTICLE CRUSHING

Phase III fuel particle crushing was successfully completed using weak acid resin (WAR) type TRISO coated fissile fuel particles burned back to the SiC coating. Depleted uranium was used in the manufacture of these fuel particles as they were made in the developmental fuel production pilot plant. The particles contained 22% $UC_3O_{0.5}$, 32% carbon, and 46% SiC.

The size distribution is shown in Fig. 11. Inspection of Fig. 11 shows that about 6 wt % of the fuel particles are less than 500 μ m (0.0197 in.) in diameter. Previous experience has shown that setting the roll crusher gap slightly larger than the smallest particles to be crushed will result in high crushing efficiencies (>99%) while minimizing overcrushing. A roll pair was available to give a 495- μ m (0.0195-in.) roll gap, as measured by the 3175- μ m (0.125-in.) solid solder technique. Using this gap gave 100% crushing efficiency, with a size distribution after crushing as shown in Fig. 11. The crusher roll speed was 36 rpm with 250 W required by the motor during crushing. The material throughput was 920 g/min.

Pertinent properties of the crushed particles were as follows: angle of repose 22°, bulk density 1.1 Mg/m³, and tap density 1.4 Mg/m³.

The material was then tray-burned in a muffle oven to burn away the carbon inner coatings and to convert the uranium to U_3O_8 . Size analysis after tray burning is shown in Fig. 11. The material properties were: angle of repose 34°, bulk density 1.3 Mg/m³, and tap density 1.6 Mg/m³.

Fig. 11. Size distributions, crushed WAR particles

No inert gas was used or needed during the crushing tests. A slight warming of the material was noted initially (about 5°C), but this heat soon dissipated.

Start under load was achieved with 100 g of fuel particles.

Burning tests of crushed WAR particles in the 0.10-m secondary burner were completed prior to the end of the fiscal year. No problems are foreseen in handling the material as processed by the roll crusher. The high SiC content (46% as compared to 22% for FSV fertile particles) will add a large degree of safety to the burner operation since it serves as inert fluidizing media.

5.3. CRUSHER OPERATION - SEQUENTIAL BURN

Twenty LHTGR-type fuel elements were used in a sequential operation of the pilot plant systems. These elements were (1) crushed in the fuel element size reduction system, (2) the graphite was burned off in the primary burner, (3) the remaining fuel particles were classified in the zig-zag pneumatic classifier, and (4) a portion of the classifier TRISO fissile stream was processed through the particle crushing and secondary burning stages. This provided feed for each of the systems which was typical of that produced in a pilot-plant operation. Previously, feed materials were specially made for each system, and they may or may not have been processed through the previous systems.

As part of the sequential pilot plant operations, 49.3 kg of TRISO-coated WAR particles and 9% fuel element graphite were crushed and burned in the 0.20-m secondary burner system. The fissile fraction of classified primary burner product was used as feed for the fertile roll crusher. Material weight was 49.3 kg. Composition was 9 wt % carbon, 6 wt % ThO_2 , and 85 wt % TRISO WAR particles. This material was fed through the double-roll crusher to yield a crushed feed size distribution as shown in Fig. 12.

Fig. 12. Size distribution of feed and product from sequential operation run using 0.20-m secondary burner

6. CRUSHER DRIVES AND BEARINGS

Drives in the particle crushers were powered initially by direct current electric motors to permit varying motor speeds and changing the crushing rates, thus establishing the relationship between roll speed and crusher efficiency. From these tests, a single operating speed could be determined for particle crushing. Power calculations using then-known data were compared with prior test results and power demands on similar equipment. It appeared that a 560-W (3/4-hp) drive motor would be satisfactory. Due to the many uncertainties in the calculations, however, provisions were made to permit upgrading the drive to 746 W (1 hp) by simply replacing the 560-W (3/4 hp) motor with the more powerful unit.

Early in the testing, the crusher drive motor created problems by stalling. The cause was attributed to crusher manufacturing inaccuracies. Later, a roll bearing overheated, which caused the motor to overheat and stall. The bearing was found to be low on grease. After cleaning and regreasing, the bearing functioned for the remainder of the run, but was in poor condition. The unit was carefully disassembled, and assemblies and components were examined for evidence of failure, wear, or other defects. Two bearings were selected and forwarded to the bearing manufacturer's laboratories for analysis of wear and general condition. Grease samples from each bearing were tray-burned in a muffle oven to remove all hydrocarbons, graphite, and fuels, and to expose any metallic and silicon carbide residuals. Finely divided foreign material in varying amounts was found in the bearing grease. Thus there existed a potential for accelerated bearing wear, overheating, and eventual failure. The bearing manufacturer later confirmed that apparently the silicon carbide dust did get into the bearings, causing excessive wear, which, coupled with an unnecessarily high bearing preload, contributed to the bearing overheating. Their recommendations were to improve the sealing for the bearings to exclude the dust, and to reduce the bearing preload by at least one half [to 0.51 m-kG (45 in.-lb) torque].

The crusher was reassembled using two replacement bearings. Care was exercised not to overlubricate, which reduces bearing efficiency. The bearing shafts were preloaded to 0.81 m-kG (70 in.-lb). (The manufacturer's recommendation of 0.51 m-kG (45 in.-lb) was received after reassembly.) A 746-W (1-hp) dc drive motor was obtained to replace the 560-W (3/4-hp) drive and to furnish more power and avert stalling. The crusher was placed into service crushing feed for the secondary burner runs.

From continued operation and testing of the particle crusher, it was determined that the installed 746-W (1-hp) drive was not sufficiently reliable for prototypical operation. It was observed to be incapable of starting under a full load of product and to stall out when product was discharged to the crusher while it operated under no-load and full operating speed conditions.

The drive requirements for the particle crusher were recalculated to include new and conservative torque values for the passive particle load, crushing work, and active maximum bearing preloads. Since the particle crusher operates at a single speed, a variable speed drive was not needed and the drive was changed to an ac squirrel-cage induction motor, NEMA Class B. With constant speed roll operation, an ac motor is a better drive choice since it operates best at a single speed. The standard squirrel-cage induction motor (NEMA Class B) has operating characteristics that are attractive to the crusher drive. These motors will deliver two to two-and-one-half times the operating torque at start for start-under-load conditions, and the torque rises sharply with modest decreases in speed from full operating speed (when the load is applied, the speed decreases and the stall torque rises). The ac motors are also smaller and lighter than their dc counterparts, and have simplified electrical controls.

To provide an estimation of the power requirements, the particle column load, the work of crushing, and the bearing preloads were considered. This indicated the need for a 1492-W (2-hp) drive at the roll speed of 40 rpm. A new single speed ac electric motor and reducer were purchased,

adapted, and installed in the system. This new arrangement cannot be fully tested beyond the simple initial testing until the sequential burner runs are performed.

During the refitting of the crusher to a more powerful drive, two of the bearing installations were modified to provide improved dust seals. One modification included the installation of Nilos seals on both bearings. The Nilos seal is a metallic membrane located between the inner race and the roll shoulder and seals by spring-loading on the outer race. This puts two mechanical seals in the path of influxing debris. The mounting of one Nilos-equipped bearing was altered to permit the introduction of a positive gas purge, presenting another obstacle to entry of dust into that bearing. One crusher is now equipped with two bearings sealed by single seal rings, a single bearing with a Nilos second seal, and a similar double sealed bearing with a positive gas purge. The efficiency of these improved sealing arrangements will be evaluated after sequential test runs.

The dimensional checks of the crusher parts and assemblies performed during retrofitting to the larger motor revealed numerous discrepancies, which, wherever possible, were corrected prior to reassembly. However, it was discovered that the parallelism of the side body assemblies could be disturbed by the pressure exerted from preload torquing the bearings in place. This was possible by the manufacturing tolerances between the pins and holes aligning the side bodies with the end bodies. A spacer bar was designed to prevent the inward and outward motion of the side bodies, which ensured the maintenance of precise parallelism while preloading the bearings. These spacers were installed prior to the latest assembly of the crusher.

7. ROLL WEAR

The crusher rolls for the particle crusher are periodically removed, decontaminated, and examined for evidence of wear. The roll surfaces were inspected using a recording surface analyzer, which scans the surface for roughness and contour change. Roll diameters were measured in 20 places and compared with previous measurements. Photographs were taken of interesting surface sites for comparison with previously made pictures.

The crushing surfaces of the hardened AISI 1018 roll and the AISI 4340 roll were very similar in appearance at each observation after the adherent graphite and carbon coating had been removed with emery paper. Both roll surfaces contained numerous unidentified anomalies, which appeared as clustered pits. These anomalies and the nominal roll surfaces were scanned with a brush surface analyzer for roughness, depth of pits, grooves, etc., and pitted areas were explored.

Initially, the roll surface roughness increased from RMS 16 to RMS 28, and then appeared to stabilize. The depths of the pits remain unchanged although the pit breadths are apparently increasing, as might be expected. Some of these changes may be attributed to the hand scouring of the roll crushing surfaces with emery paper to remove surface contamination.

The crushing surfaces of both rolls at the ends have become slightly burnished but still possess sharp, unbroken edges. The pitted areas are typically relatively shallow [<0.051 mm (<0.002 in.) deep] although quite wide [5.1 mm (0.20 in.)] and rough (RMS 112), for example. The reasons for these pitted regions are unknown, and efforts are continuing to determine them.

Using successive photographs of the pitted regions of the roll surfaces, certain interesting sites have been identified and compared. The characteristics of the sites have remained virtually unchanged, and the sites are readily located and identified.

The results of roll examination to date indicate no positive definable trends in wear of the roll crushing faces from the crushing of the silicon-carbide-coated fuel particles. There are no identifiable differences between the carburized and hardened AISI 1018 roll and the surface-hardened AISI 4340 roll.

8. FUTURE PLANS

The test program for the fuel particle crusher called for the performance of experimental work to ascertain that the crusher achieved the design objectives in the design criteria (Ref. 3), and provided data and observations identified in the activity plan (Ref. 2).

The double-roll crusher with a fixed crushing gap performed as expected during testing and met the design requirements. As a result of crusher operations, certain modifications and alterations to the design have been indicated as follows:

1. Reduce manufacturing and assembly complexity and cost by using a new housing design.
2. Increase the wear life of the roll end plates by selective hardening or other means.
3. Provide thermal expansion capability, simplify the bearing preloading, and assure improved reliability by using a modified bearing design.
4. Increased bearing protection by introducing improved bearing seal methods.
5. Assure restart capability when fully loaded and avert stalling under a rapidly applied full load by upgrading the drive system.
6. Extend roll wear life by altering the roll hardness, materials, or heat treatment.

Each of these topics has received initial attention during particle crushing for burner operations, except for the new housing design, bearing changes, and roll alterations to improve wear life.

Future planning calls for a complete design evaluation of the existing particle crusher to assess its suitability as a prototype to the HRRF, and to recommend alternatives to the existing design, where needed.

Subsequently, the fuel particle crusher will be completely redesigned to reflect recommendations arising out of the design evaluation and the continuing operation of the crusher. The effectiveness of the current upgrading of the drive system to a higher horsepower ac system, of purged and shielded bearings, and of implanted ceramic wear rods in the crusher side plates will be evaluated as the data become available. These changes will be incorporated into the crusher redesign, where appropriate. A new test program for evaluation of the new design will then be devised and the equipment proof tested.

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